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MODELLING OF MAINTENANCE STRATEGY OF OFFSHORE WIND FARMS BASED MULTI-AGENT SYSTEM

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ABSTRACT

The maintenance of offshore wind turbines is a complex and costly task which represents a barrier to the development of this source of energy. The combination of the size of the farm and the size of the turbines themselves, the distance from the coast and difficult meteorological conditions make the choice of maintenance strategy difficult. Several modern maintenance techniques have been tried in order to reduce cost and time of maintenance. In this paper we propose a hybrid model of maintenance based on multi-agent systems, which allows for the modelling of systems with dynamic interactions between multiple parts. A multi-criteria decision algorithm has been developed to allow analysis and choosing of different maintenance strategies. A cost model including maintenance action cost, energy loss and installation of monitoring system cost has been presented. A simulator has been developed using NetLogo software and this is presented along with initial results at the end of this paper. These results show that employing a new hybrid maintenance strategy which we propose could increase wind farm productivity and reduce maintenance cost.

Keywords: Offshore wind turbines, renewable energy, multi agent systems, maintenance, failure modes, simulation

1 INTRODUCTION:

An offshore wind farm is defined as a collection of wind turbines and associated equipment to generate electricity from wind power. The factors influencing choice of site are principally: distance from coastal facilities, water depth, and wind quality [1]. This source of energy has the potential to become the biggest source of energy in the future [2][3]. Europe is the world leader in developing such farms from the Nordic countries, such as Sweden and Denmark, through to Holland [4]. Several countries are interesting in this kind of energy, such as France, which expects to have operational farms developed by 2018 according to [5].

The biggest obstacle to the ongoing development of this source of energy is the high cost of installation, operation and maintenance compared with other sources of energy [4]. The maintenance of offshore wind turbines is difficult and expensive especially when site weather conditions are hostile [6]. As a result, it is estimated that the cost of maintaining offshore wind turbines makes up between; 25% to 30% of the total kWh cost of electricity, compared with 10% to 15% of onshore terrestrial sites. This high cost is extremely sensitive to the type of maintenance strategy adopted: for example preventive maintenance costs

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between 0.003 and 0.006 (€/kWh) while corrective maintenance is between 0.005 and 0.01 [7]. Reducing maintenance costs is a key step in establishing the future of offshore wind farms.

Several researchers have studied the optimization of maintenance strategies for offshore wind farms. For example [8] (2011) propose a strategy based on a permanent base (using a hotel boat with a permanent repair team) within the farm allowing for rapid interventions in the case of a breakdown. [7] Suggest locating several large cranes within the farm to reduce maintenance time for large heavy pieces of equipment such as gear-boxes. They have shown that even having multiple large cranes of 50 MT costing euro 150k is less expensive in the long term than traditional repair voyages. [9] and [10] have put forward a strategy based on the risks and costs of avoiding corrective maintenance.

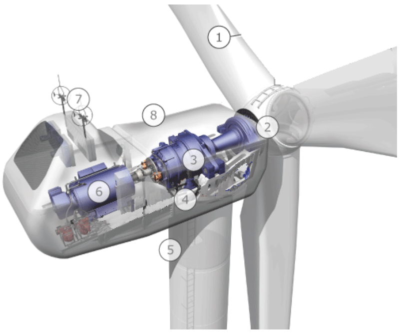
The Modelling and simulating of offshore wind farms is an essential task in establishing an optimum maintenance strategy. The involvement of several actors in the operation of the system makes the modeling task both complex and difficult. Several research teams are currently developing simulations covering one or several parts of the system. [11] set out a restricted model using Petri-nets, but suggest several possible uses and developments of their model. [6] (2011) have created a discrete event simulation model based on (Discrete event system specification (DEVS)) including each component of the turbine. Their results show the advantages of a condition based strategy over a preventive strategy, although their study was concentrated on the gearbox. Pieterman et *al* [8] have developed a historic based model to calculate maintenance costs examining the transport system and have established an optimal solution based on the type of breakdown. All these earlier studies have been confronted with the insurmountable problem of the complexity of establishing a correct strategy for offshore wind farm maintenance, due to the number of uncontrollable factors in the system, the weather conditions, human factors and the difficulty of access.

Using a distributed system, specifically Multi-Agent System (MAS), is an interesting choice for the modelling of this type of problem. Several studies [12] [13] are interesting in the use of MAS approach for the offshore energy production because the conventional methods are unable to ensure the required level of safety and performance of these systems [14]. This type of model allows us to model each agent in the system independently, and subsequently add the interactions and relationships between the different parts of the system [15].

This paper puts forward a multi agent system based model for offshore wind turbine maintenance bringing into account a variety of potential failure modes in the turbine. A new maintenance strategy is proposed which enhances performance and reduces cost. This paper is organized as follows: in section 2 we set out the types and causes of the most significant failures of the parts of the wind turbine; in section 3 we present the multi agent model with a description of each agent, and its interactions with the others and the developed cost model; section 4 describes the simulation based on our model and a comparison between our hybrid maintenance strategy and other types of strategy (systemic and condition based). We conclude the paper with a more general discussion and considerations for further research.

2 FAILURES OF OFFSHORE WIND TURBINES

One significant advantage of offshore wind turbines is the ability to install much larger turbines (eg blade length in excess of 90m) enabling power production of 6MW and above [16]. Such large size and extreme weather conditions increases the difficulty of Operation & Maintenance (O&M), even though the cost per kW.h reduces with the size of the turbine [17].



1 => Blades
2 =>Rotor
3 => Gearbox
4 => Hydraulic system
5 => Yaw system
6 => Generator
7 => Controller
8 =>Electrical equipment

Figure 1: Principal component of a wind turbine

A study of a Danish wind farm [18] has shown that 60% of breakdowns concern the electrical system, the gearbox, the directional control system, the generator, and the hydraulic system. In the rest of this section, we will examine the types and causes of breakdown for each of these areas.

2.1 Failure of the electrical system

The principal types of failure in the electrical system are failures in the armatures, short circuits and damage to the electrical components, transformers and wiring breaks [19]. The most significant causes of these breakdowns are shorting caused by power surges, poor installation, and technical faults in electronic components (e.g. resistors and capacitors).

2.2 Failure of the yaw system

This system controls the orientation of the nacelle (turbine housing) in order to follow the wind direction. In general, one encounters problems with cracking of yaw drive shafts, failures of the rotational bearings and fixings, and fractures of the gears [19]. These failures are due to icing on the nacelle, high vibration during periods of strong winds outside safe operating conditions, and failures linked to breakdown in the motor unit [20].

2.3 Failure of the gear box

The gearbox, with its vital role, also represents the weakest part in the turbine experiencing the most frequent breakdowns; replacement is complicated and time consuming (approximately 5 days [7]). The principal failure modes are associated with rotational issues and broken gear teeth [21]. These are frequently the results of particulate contamination, frequent stopping and starting of the turbine, and operating outside safe wind speeds [19].

2.4 Failure of the hydraulic system

Hydraulic components are used in multiple high pressure locations within the turbine such as the directional control, the gear box, braking systems, and so on. The issues surrounding fluid leakages from hydraulic components are a well known source of failure. They are essentially due to frequent changes in temperature, corrosion, vibrations, bad design and poor component quality. Bad installation of hydraulic systems is responsible for 60% of failures [22].

2.5 Failure of the turbine blades

The blades (either two or three), are directly responsible for converting wind energy to mechanical energy (and subsequently electrical) due to their aerodynamic design. We can generalise and group under blade failures such phenomena as breakages, splits, and vibration damage. The principal causes are wind turbulence, uncontrolled rotation and operation, electrical storms and manufacturing faults [23].

2.6 Classification of causes of failure

With regards to classifying the causes of failure of the different components within the turbine, we have used the following 3 broad areas: the weather; humane operation errors (human); and product quality or technical effects (technical) as repsented on the Figure 2. Developing a maintenance strategy has to take into account all these elements. The model which we describe below in this paper will take into account the effects of the weather on the turbines, the different failure types due to the underlying faults of construction or installation.

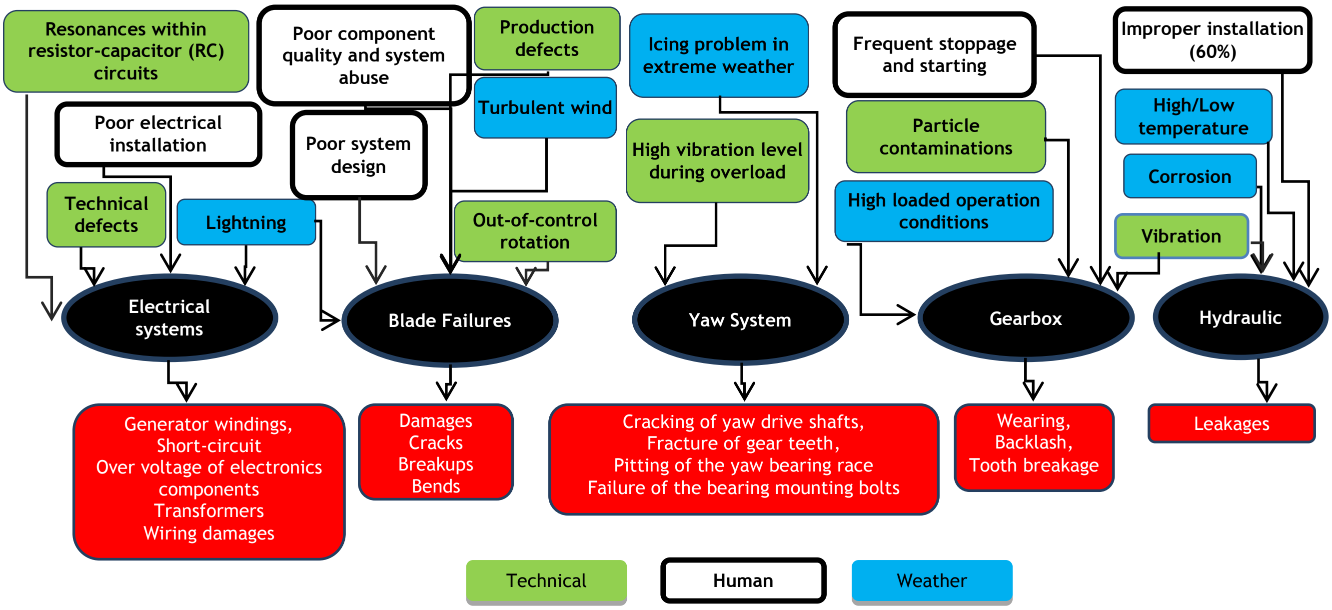


Figure 2: Principal cause of turbine failures

3 MULTI-AGENT-SYSTEM BASED MODEL

The maintenance of an offshore wind farm is a complex task because it happens on several locations and it is subject to constraints associated with the weather, and the availability of appropriately qualified human resources, spare parts, appropriate boats and cranes. The success of a O&M task depends on the intervention of several parts within the system. The decomposition of the system into several interacting parts and considering each part separately; is a very effective way to avoid complexity and make the modelling task easy. Using a multi-agent-system architecture is an interesting and useful method for modelling and simulating such a system.

3.1 Global model

We have divided the system into 5 interconnected parts, each part consisting of one or more autonomous agents, as depicted in Figure 3. We have considered 5 types of agent:

- Turbine
- Maintenance strategy
- Resources
- Monitoring
- Weather

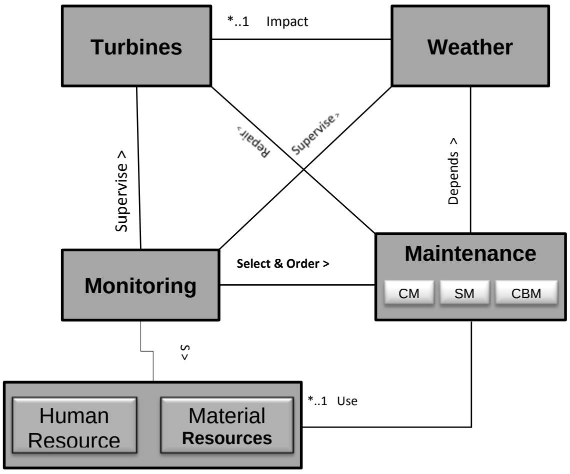


Figure 3: Multi-agent modelling architecture

We will describe in the following sections the behaviour and composition of each agent and justify their naming.

3.1.1 *The agent "Turbine"*

Each turbine is represented by an autonomously communicating agent. We consider several typical techniques associeated with the production of electricity according to the speed of the wind V_s principally:

- V_{cin} the cut-in wind speed representing the lowest wind speed at which electricity can be generated.
- V_{cout} the cut-out wind speed which is the maximum allowable for safe operation. The turbine is shut down if the wind speed exceeds this value.
- V_r the rated wind speed which is the minimum wind speed at which each individual turbine can produce its maximum energy.

The power generated by a turbine follows the power curve shown in Figure 4. According to the work of [24] the power generated by a turbine in a wind speed of V_s is calculated by the following equation

$$\boldsymbol{P_r = \begin{cases} 0 \quad if\ 0 \le V_s < V_{cin} \\ P_r\left(a + b \cdot V_s + c \cdot V_s^2\right) \quad if\ V_{cin} \le V_s < V_r \\ P_r \quad if\ V_r \le V_s < V_{cout} \\ 0 \quad if\ V_{cout} \le V_s \end{cases}}$$

(1)

Where P_r is the rated power output of the wind turbine. The parameters a,b and c in equation (1) are obtained from the following equations:

$$a = \frac{1}{(V_{cin} - V_r)^2}\left[V_{cin}(V_{cin} + V_r) - 4V_{cin}V_r\left(\frac{V_{cin}+V_r}{2V_r}\right)^3\right]$$

$$b = \frac{1}{(V_{cin} - V_r)^2}\left[4(V_{cin} + V_r)\left(\frac{V_{cin}+V_r}{2V_r}\right)^3 - (3V_{cin} + V_r)\right]$$

$$c = \frac{1}{(V_{cin} - V_r)^2}\left[2 - 4\left(\frac{V_{cin}+V_r}{2V_r}\right)^3\right]$$

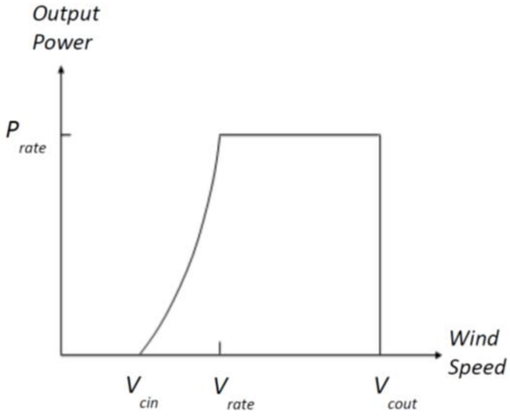


Figure 4 : Power curve.

The wind speed is measured by meteorological stations often situated at ground or sea level. This measured speed is not the same as the speed at the height of the nacelle and this difference depends on the nacelle height, the height of the meteorological station, and the type of terrain separating the station and the turbine [13]. The wind speed at the turbine height is given by the following equation derived from [25] [26]:

$$V_s = V_0 \left(\frac{h}{h_0}\right)^{\alpha}$$

Where:

h: The nacelle height

h_0 : The measurment point height

V_s: The wind speed anemometer height h (nacelle) at the turbine location

V_0 :The wind speed at hub hright h_0

α : The wind speed power law coefficient, this value mainly depends on the local geographical terrain.

We suggest several performance indicators for the turbine to measure the risk of breakdown, the nearness to degradation for each component and an indicator for the health of each turbine. Table 1 describes the indicators we have used and their definitions

Table 1: Performance indicators of a turbine

Indicator	Description
EHF (Equipement Health Factor)	It is a global indicator of the health state of the tubine. It varies through the time and after a O&M task or after a weather enevets. It is variating between 0 (very bad) and 10 (very good)
MAR (Material At Risk)	It is a global indicator of the health state of the turbine. It varies through the time and after a O&M task or after a weather event. It changes between 0 (very bad) and 10 (very god)
IsD (Inscpection Delay)	The time since the last inspection or O&M event.

Each turbine has several operating states which affect the quality and quantity of power generated. We have identified 4 such operating states:

- Normal functioning: The turbine is in good health with an $EHF \in [8;10]$ with a probability of failure of 5%.
- Degraded functioning: The turbine is capable of producing 80% of its maximum with an $EHF \in [4;8[$. The probability of failure is 20%.
- Critical functioning: The turbine can only produce 30% of its maximum. The $EHF \in [1;4[$ and the probability of failure is 70%.
- Fail: The turbine is stopped, requires corrective maintenance and its $\in [0;1[$.

In order to define the behaviour of the turbine and its interactions with its environment, we have defined two functions:

- Producing:This defines the power being generated
- Degrade: This updates the indicators of turbine performance. The different components have a probability of failure which follows a Weilbull distribution with 3 stages with different parameters for each component. We have taken into consideration the 5 most important components, being the electrical system, the yaw system, the gearbox, the hydraulic system and the blades. The failure and stoppage of any one part causes the stoppage of the whole turbine, with the reliability of the turbine given by the following formula:

  $$R_{tur} = R_{es} \times R_{ys} \times R_{gb} \times R_{hs} \times R_{bl}$$

  Where:
  R_{es}: the reliability of the electrical system
  R_{ys}: the reliability of the yaw system
  R_{gb}: the realiability of the gearbox
  R_{hs}: the reliability of the hudraulic system
  R_{bl}: the reliability of blades

Some other agents are able to affect the performance parameters of the turbine, such as that the weather agent or the maintenance agent. Others are able read only this parameters such the monitoring agent.

3.1.2 The agent "Weather"

The variations in the meteorological conditions are represented by the agent "weather". This is characterised by wind speed V_s, wave height, H_s, Lightning, L_g, and visibility $Visi$. These parameters are generated by the apropriate statistical distribution (Weibulle for V_s and Rayleigh for H_s) which change their parameters according to the season. We have defined two weather windows which restrict the types of possible maintenance task able to be performed.

- Safe window: this includes all weather conditions which allow for safe performance of tasks by technicians and experts with easy marine access to the turbine. These conditions are defined by $V_s \leq 8\frac{m}{s}$,$H_s \leq 1.5\,m$,and $Visi \geq 5\,km$.
- Wide window this includes weather conditions in which only experienced personnel in both access and boat handling can perform tasks. The limits of this window are $V_s \leq 12\frac{m}{s}$, $H_s \leq 2\,m$ and $Visi \geq 2\,km$

The behaviour of the agent "Weather" is defined by an *"update"* function which allows us to generate values characteristic of the weather, and a function *"degrade"* which represents the effect of the weather on the turbine performance.

3.1.3 The agent "Resource"

We have defined two types of resource agent: materials and human. The agent "human resource" is characterised by the number of engineers (*Ing*), the number of technicians, (Tech), and the collective experience of the team (*Exp*).This agent trials a number of different types of maintenance intervention and team availability is updated daily. (the function update_R).

The agent "materials resource" includes a number of tools necessary to carry out a maintenance task. We distinguish between 3 types of boat (large, medium and small) two types of crane (2MT and 50MT) and spare parts. The behaviour of this agent is generated by degradation and maintenance functions, which represent respectively the degradation and repair of the equipment.

3.1.4 The agent "maintenance"

O&M tasks are represented by a collection of corrective preventive and condition based maintenance agents. Each type is characterised by its own cost, requirements in terms of other resources and operating conditions (weather window, breakdown type).

- Preventive systemic maintenance (SM): This maintenance type is most used due to its *reasonable* cost. If we are only concerned with the "health" of the turbine, this strategy is the most *effective*. Often lubricants and other components have an expected life of less than a year and are replaced and r*egular inspections* carried out. This intervention type takes between 1 and 2 days and requires one expert and two technicians. It is generally carried *out according to a schedule* and when weather conditions permit.
- Preventive condition based maintenance: This is a strategy driven by information about the performance of the turbine. This strategy is generally used in conjunction with a fault tree to diagnose problem causes. It is recommended to do the tasks planned for systemic maintenance when the condition-based maintenance is performed.
- Corrective maintenance : This type of maintenance is performed to repair a significant failure when the turbine is stopped. This is a very costly strategy and requires significant material (eg subcontractors, medium boat, heavy cranes) and possible delays of between 2 and 5 days to perform the necessary tasks. Hence, this strategy is not recommended. In our model, this strategy is not used unless the turbine is broken.

The different types of maintenance agent require a careful management of the interrelationships between facts and potential intervention dates to increase the efficiency of maintenance. We have assumed that the action of maintenance is to restore the turbine to its "normal" condition, and to restore all operational indicators to their required state before the breakdown. The behaviour of the maintenance agents is given by the following functions:

- Resource demand: this combines the necessary material and human resources together in order to carry out the specified task
- Repair: this function sets in motion the repair of the turbine. For the duration of the task, the turbine is stopped and in maintenance mode
- Return resources: once the maintenance task is completed, this function returns the resources that have been used, allows the turbine to restart and self-destructs.

3.1.5 The agent "Monitoring"

This agent is responsible for planning the maintenance tasks and prioritising between the various turbines, which need to be maintained. It controls the state of the other agents and ensures each turbine receives the appropriate maintenance.

The choice of turbine is decided on a number of criteria. We have defined the following criteria: (1) the date of the next preventive maintenance, (2) the level of risk of a failure or degradation, and (3) the state of health of the turbine. The choice of maintenance type is dependent on the criteria that are used to select the turbine. If the turbine is chosen for maintenance on a time basis, then the task type will be systemic (SM), if it based on state or risk and EHF level the task type will be conditional (CBM). If the turbine brakes down, then the relevant corrective maintenance (CM) is chosen. This agent can order several maintenance tasks at the same time. Figure 5 describes the algorithm used by this agent to choose the turbine to repair and the appropriate maintenance type.

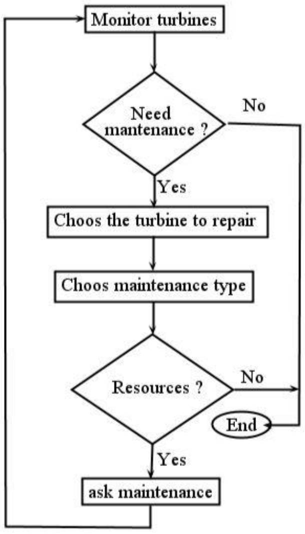


Figure 5: Monitoring agent functioning

3.1.6 Cost model

The maintenance cost is an important criterion in the decision making of de maintenance strategy. It depends on several parameters such as the type of failure, the type of maintenance, the duration of maintenance, the weather conditions, and the installation cost of the maintenance facilities [27]. The adopted cost maintenance model is a parameter defined by several agents, for instance: the maintenance agent generates a cost at every maintenance action; this cost is depending of the maintenance type chosen and the maintenance contact. The used resources increases this cost. When the turbine is stopped of functioning in a degrade mode, the produced energy less than the nominal one, this loss of production is also considered as a cost due to the maintenance strategy.

We consider that the corrective maintenance task is more expensive than a preventive maintenance task; according to [7] we consider that the cost of a corrective maintenance is equivalent to tow systemic maintenance tasks. If the condition-based maintenance is used the cost of the installation of monitoring system is add to the global cost of maintenance and it depending of the EHF of the turbine.

The global cost of maintenance over a period of time is computed as follow:

$$\begin{aligned} GC &= is_{cbm} \times C_{init} + C_{maint} + C_{e-loss} \\ &= is_{cbm} \times C_{init} + C_{pm} + C_{cm} + C_{down} + C_{dg} \\ &= is_{cbm} \times C_{init} + C_{sm} + C_{cbm} + C_{cm} + C_{down} + C_{dg} \end{aligned}$$

Where:

is_{cbm}: a Boolean indicator of the presence of monitoring system for condition based maintenance

C_{init}: the cost of installation of the monitoring system for the condition based maintenance

C_{maint}: The global cost of maintenance tasks, it is composed of the cost of corrective maintenance (C_{cm}) and the cost of the preventive maintenance (C_{pm}). The latest is composed of the cost of the systemic maintenance (C_{sm}) and the cost of condition based maintenance (C_{cbm}).

C_{e-loss}: the cost due the loss of energy production. It is composed of the loss of energy when the turbine is stepped for maintenance or a failure (C_{down}) and the loss due to the degrade functioning of the turbine (C_{dg})

The global cost van be written as follow:

$$\begin{aligned} GC = {} & is_{cbm} \times C_{int} \\ & + \sum_{tr=1}^{tr=NT} \left(\sum_{i=1}^{i=N_{sm}} C_{sm}\,(i) \cdot X_{sm}(tr,i) \; + \sum_{i=1}^{i=N_{cbm}} C_{cbm}\,(i) \cdot X_{cbm}(tr,i) + \sum_{i=1}^{i=N_{cm}} C_{cm}\,(i) \right. \\ & \left. \cdot X_{cm}(tr,i) + \sum_{i=1}^{i=N_{cbm}+N_{cm}+N_{sm}} C_e \times D(tr,i) + \sum_{i=1}^{i=N_{cbm}+N_{cm}+N_{sm}} C_e \times DG(tr,i) \right) \end{aligned}$$

Where:

NT : the number of turbine in the farm

N_{sm}, N_{cbm} and N_{cm}: the number on systemic, condition-based and corrective maintenance respectively during the considered period (T unite of time)

X_{sm}, X_{cbm} and X_{cm} are the decision variable where it is equal to

$$\begin{cases} 1 \text{ if the turbine } tr \text{ is selected for maintenance at the instant } i \\ 0 \text{ other ways} \end{cases}$$

$D(tr,i)$ is an indicator of the state of the turbine tr $\begin{cases} 1 \text{ if the turbine } tr \text{ is stopped at the instant } i \\ 0 \text{ other ways} \end{cases}$

$DG(tr,i)$: measure the degradation level of the turbine tr at time i. It is computed as follow:

$$DG(tr,i) = \frac{10 - EHF(tr,i)}{10}$$

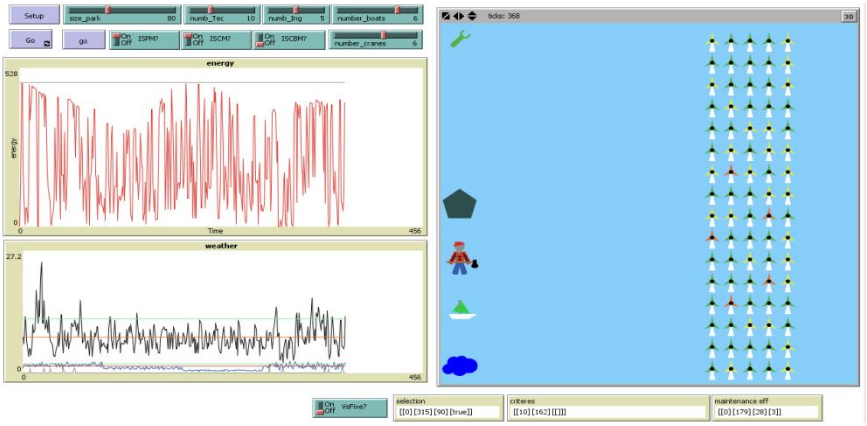
The cost is defined as a global variable increased by each concerned agent in the simulator.

3.1.7 Relationships between the various "agents"

An offshore wind farm is made up of a certain number of turbines, affected by the agent "Weather" impacting on both production and degradation. The monitoring agent assesses all the turbines and reports on those which are broken or which need to be maintained. It selects the best possible maintenance to perform and assesses whether the agent "Maintenance" is available; ie has sufficient resources and appropriate weather conditions to carry out the required tasks. Before scheduling maintenance, the monitoring agent checks the availability of the required resources and the weather state. The agent "Maintenance" then requests the necessary resources. Once the task has been performed it returns *the resources to* store.

4 SIMULATION

We have used the logical program NetLogo to develop a simulation based on the model defined in the previous section. NetLogo is a multi-agent programmable modelling environment. It is particularly well suited for modelling complex systems evolving over time [28].



size_park 80

numb_Tec 10

numb_Ing 5

number_boats 6

ISPM? On

ISCM? On

ISCBM? Off

number_cranes 6

ticks: 368

VsFixe? Off

selection [[0] [315] [90] [true]]

criteres [[10] [162] [[]]]

maintenance eff [[0] [179] [28] [3]]

Figure 6: The wind farm simulator developed with NetLogo

The objective of the simulation is to define the optimum maintenance strategy, which allows for the generation of most power *at lowest cost*. Using the model allowed us to test various maintenance strategies comparing various farm performance indicators over a long period. We have the opportunity to observe several performance indicators including power production, the number of working turbines, the health state of each turbine, the cost of maintenance actions, the cost of electricity produced.

We have considered tow evaluation criterion, which are the generated electric energy and the cost of the maintenance. Each parameter of the simulation can be observed. In addition to the evaluation criterion, we could also observe the weather state, wave height and lightning strikes. The simulation step was one day. The values chosen for each of the parameters was the average for each day. Figure 6 sets out the environment of the simulation. We can both initialise and start the simulation as desired. We can vary various parameters such as the number of turbines, the resources available (eg engineers, technicians, boats, cranes, and spare parts). The state of health of each turbine is represented by a different colour: green for normal functioning, yellow for alert, orange for critical, and red for broken. When maintenance is being carried out, the colour of the turbine, become black. We have assumed big wind turbine characteristics with a nominal maximum power output of $P_r = 6\,\mathrm{MW}$; start up wind speed $V_{cin} = 4\frac{m}{s}$; rated wind speed $V_r = 14\frac{m}{s}$; and safety stop maximum wind speed $V_{cout} = 25\frac{m}{s}$[1].

Figure 6 shows a simulation carried out over the period of one year. We observe that the total power output of the farm is highly dependent on wind speeds. We used historic data obtained from Le Havre airport, situated on the English Channel (La Manche) coast. We have assumed that this wind speed is typical of general conditions. For wave height, we have used Rayleigh's distribution, with a parameter σ according to the season [29]. As the NetLogo software does not have such a function, we have used the following equation to generate wave height using the uniform distribution available on NetLogo:

$$H_s = \sigma \times \sqrt{-\log U}$$

Where :

U is a uniform random variable taking values between 0 and 1.

The lightning is generated following a uniform distribution regarding the season.

To identify the effect of the particular strategy on power production, we have run the simulation with a constant wind speed over the year. Meteorological variations (wind, wave, and lightning) have been used to choose whether or not to perform the maintenance task, and to impact on the degradation of the turbine.

4.1 Results and discussions

We have examined 3 types of maintenance strategy to compare the effect of each strategy on overall power production. The strategies adopted were:

- Systemic strategy based on pre-planned dates combined with corrective maintenance in case of breakdown.
- Condition based maintenance as required according to the health of the turbine, combined with corrective maintenance in case of breakdown.
- A hybrid strategy (combining conditional, systemic and corrective): based on the monitoring agent selecting which type of maintenance task to perform based on the turbine chosen for maintenance. If the turbine chosen has a low health state a conditional task is chosen, if selected following a breakdown a corrective maintenance task is chosen.

Both systemic and conditional maintenance are considered as a preventive maintenance task.

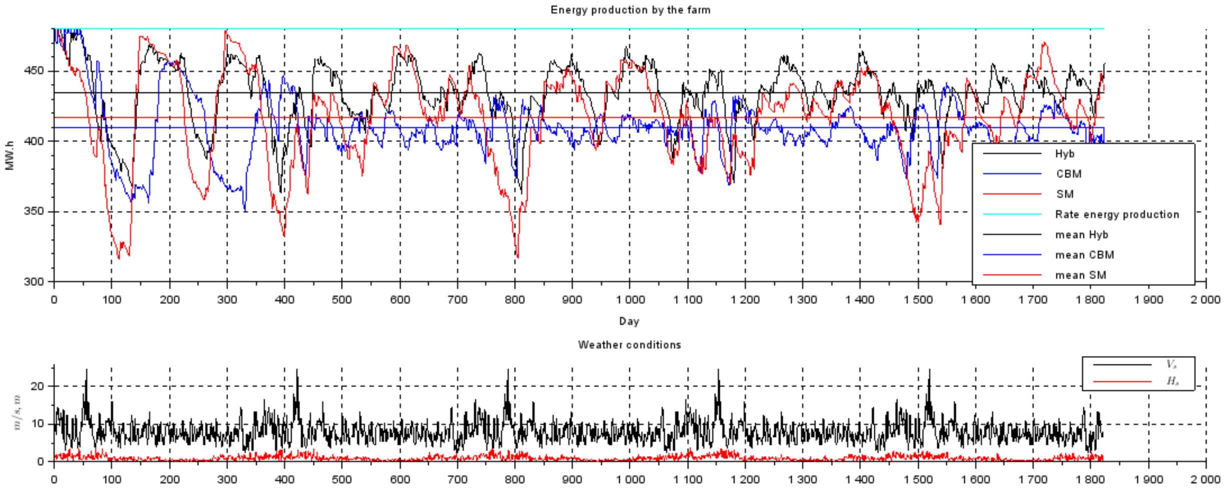


Figure 7:Total production of energy and weather condition avoer 5 yres

Figure 7 represents the level of energy produced over a period of 5 *years in the simulation*. The *modelled* farm has 80 turbines, maintained by a team of 10 technicians and 5 engineers. They have access to 6 boats, and 6 cranes capable of operating in any conditions, and an unlimited supply of material/spare parts. The duration of the maintenance task is depending of the nature of failure and the type of maintenance. The duration of a corrective maintenance varies from 1 to 3 open days, while the duration of preventive maintenance (systemic or condition based) 1 to 2 days. Figure 6 shows that the maintenance strategy and the weather conditions have a significant influence on the production of energy. The comparison of values over a period of 5 years demonstrate that a hybrid strategy which we have suggested produces the best results compared with other strategies with a production average of 90% of potential output compared with the other two strategies (87% and 85% for SM and CBM strategy respectively).

Figure 8 present the evolution of cost over the period of simulation for the three strategies. The cost is computed according to the model presented in the section 3.1.6. The obtained results show efficiency of the hybrid strategy in term of production and cost. The rented increase of the cost of the hybrid strategy is butter then the two other strategies.

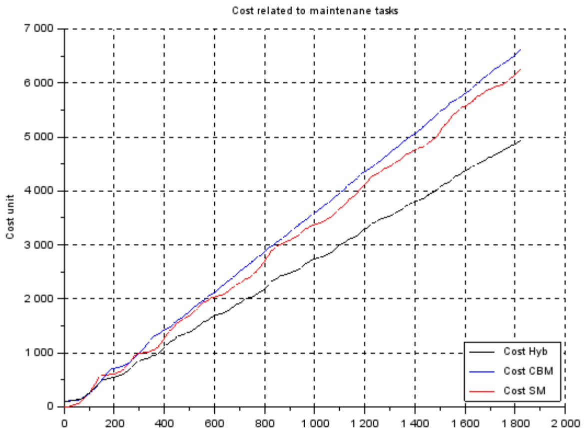


Figure 8: Cost of each strategy

Table 2 compares the number of times a maintenance task is required, and the number of times it is performed. A conditional maintenance strategy requires the least number of maintenance task with only 915 interventions but it is the most costly because the loss in production that can be observed in Figure 7. A systemic strategy has 1433 tasks of which 97 are corrective, which represents an increased number of maintenance task compared with the CBM strategy. Its cost is less than the CBM one because of the improvement of the production rate (2% more than CBM strategy). The hybrid strategy demonstrates an interesting performance for further examination; with the most important number of interventions compared with the other strategies, but it present the least costly strategy thanks to its high level of production (more than 90%). We note also that the type of maintenance task carried out most often in the hybrid strategy is systemic maintenance with approximately 2/3rd of the maintenance tasks carried out. This perhaps explains the finding that with the turbines are in good health and that they do not deteriorate as often as under condition-based maintenance, more power is produced.

Table 2: Comparison of maintenance strategy in term of cost and number of maintenance tasks

	CBM	SM	Hybrid
Number of CBM	888	0	239
Number of SM	0	1336	1225
Number of CM	27	97	14
Total	915	1433	1487
Cost	6626	6250	4947

Using a multi agent based simulator we have demonstrated the effectiveness of our proposed strategy. Our hybrid strategy produces noteworthy results for offshore turbine maintenance, which present well known maintenance difficulties and constraints. The strategy allows the choice of a compromise between the production of energy and the cost of maintenance, enabled by the choice of which turbine to maintain and what type of task to perform.

5 CONCLUSION

Energy generated by offshore wind farms is creating interest in the scientific and political communities. This paper has examined the problems surrounding choosing and implementing a maintenance strategy for these farms. In the first instance, we presented a state of the art turbine failure mode and cause. Based on this study we have defined the interaction between the different actuator in the offshore wind farms and proposed a multi-agent based model. Next, we described a simulator, which we developed to run our model, using the NetLogo program. We have proposed a cost maintenance model tacking into account the number several cost types. The last part of this paper discussed the results of the comparison between 3 maintenance strategies (systemic (SM) condition-based (CBM) and a hybrid strategy (SM, CM, CBM)).

The results clearly show that the hybrid strategy allows the most power to be generated by the farm and the least costly in spite of its big number of maintenance tasks. Reviewing these results we are able to conclude that a multi-agent approach and a hybrid strategy generates very interesting answers. The decision algorithm, which chooses which turbine to maintain, and the type of task, is based on a simple comparison of health states of all the turbines and the dates of systemic maintenance. Improving this algorithm will be the basis of our next steps in the short term. Each turbine is represented currently by an independent agent and we intend to develop our model in order to treat the turbine as a group of agents (e.g. gear box, electric system) in its own right.

Several other developments are possible in both the model and the simulator to further optimise planning and performing maintenance tasks covering other sorts of maintenance; (for example e-maintenance and more pro-active maintenance); using real rather than expected weather conditions; and reducing the simulation time period to 30 minutes rather than one day.

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